# Characterization of Indirect Coupling Mechanisms from Lightning to Underground Cavities

Matthew B. Higgins*[1], Michele Caldwell[1], and Marv Morris[2]
(1) Sandia National Laboratories, Albuquerque, NM 87123;
mbhiggi@sandia.gov ; mcaldw@sandia.gov
(2) Bolt Inc., Albuquerque, NM 87

## Introduction

The purpose of this project was to determine the electric fields induced in an underground cavity due to a lightning flash on the surface. When a lightning flash attaches to the ground, the current flows in all directions along the surface of the ground and into the soil, which is the conduction current. For a fully developed lightning flash, it is reasonable to approximate the resulting magnetic field along the surface as

$$H = \frac{I}{2\pi r}$$

over a range of distances from approximately 30 m to 1000 m. Within 30 m of the flash other factors and mechanisms will probably play a large role in any coupling, so over this region this approximation is incomplete. The physics of the coupling mechanisms close to the strike are very complex and due to the limits of this project, conduction currents were not taken into account. Also, beyond 1000 m this approximation for H may be an overestimation of the coupling. The displacement currents were disregarded since the soil can be treated as a good conductor, i.e.

$$\left(\frac{\sigma}{\omega\varepsilon}\right)^2 \gg 1,$$

where σ is the conductivity of the soil, ε is the soil permittivity, and ω is the maximum frequency of interest. Once the magnetic field on the surface is determined from a flash, the problem of coupling the field underground, at distances on the order of and larger than the penetration depth, can be considered quasi-static and one-dimensional. The magnetic fields on the surface are translated to attenuated electric fields in the sealed area of the mine using the simple analytic models.

The methodology used to measure this effect is to simulate magnetic fields in the earth by connecting a frequency variable voltage source via straight wires on the surface between ground rods at either end of the wires. The ground rods are placed a significant distance from each other, approximately 100 m on either side of the region where the electric fields are measured. The electric fields are measured over a frequency range from 10 Hz to 100 kHz. At this point we have the electric field in the underground cavity from a known linear current distribution on the surface.

## Test Methodology and Configuration

The method used to characterize indirect electromagnetic coupling into an underground cavity is shown in Figure 1. The current from the audio amplifier (which is driven by the output from the network analyzer) is driven on to a long wire above the ground which is terminated at each end with ground rods. The ground rods are placed so as to produce a current distribution in the ground that simulates a linear current drive, which then can be related to the lightning current distribution.

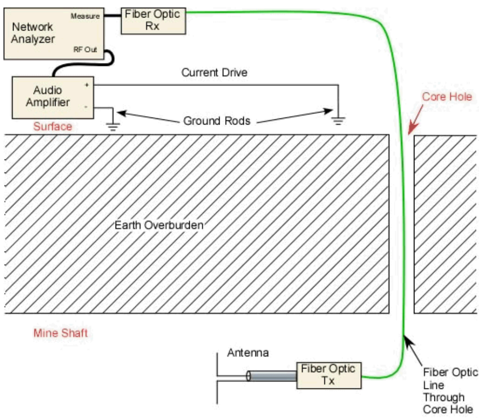


**Figure 1 In-Direct Drive Conceptual Drawing.**

Two current drive configurations were used for the indirect drive measurements. One configuration was through ground rods placed so as to drive the current parallel to the length of the underground cavity and over the center of the cavity. The surface drive wire was approximately 500 m long. A second configuration was through ground rods placed so as to drive the current perpendicular to the length of the underground cavity. In this case the surface drive wire was only 200 m long.

**Figure 2 Sandia dipole antenna in vertical polarization inside underground cavity.**

The electric field at various locations in the underground cavity of the mine was measured with an active dipole antenna connected to a receiver via fiber optics. The fiber optic receiver is connected to the network analyzer measurement port so that the signals are phase-locked in order to measure very small signals in the microVolt/meter range. The three polarizations of the electric field were measured at a total of 15 locations for both the parallel and perpendicular wire current drives. A photo of the dipole antenna in vertical polarization is shown in Figure 2. The locations of the measured electric field where approximately centered around the middle of the current drive and the distance between locations was approximately 10 m. The three polarizations measured were the vertical, P-directed (parallel to the length of the cavity), and X-directed (transverse to the length of the cavity).

## Indirect Electromagnetic Coupling Model

To calculate the electric fields in the earth induced by a current on the surface, the problem is simplified by representing the earth as a homogeneous material with a constant resistivity. The calculations for the indirect coupling model are shown below where the current drive is assumed to be of infinite length and time-varying, as more appropriate for lightning currents on the surface. These results are used to compare to the indirect measurements of the electric field in the cavity as a function of the drive current on the surface.

The current drive geometry of an infinitely long, horizontal wire placed a distance, h, above a conductive half-space is shown on the left side of Figure 3. A side view is shown on the right side of Figure 3. Similar configurations are analyzed in References 1 through 5.

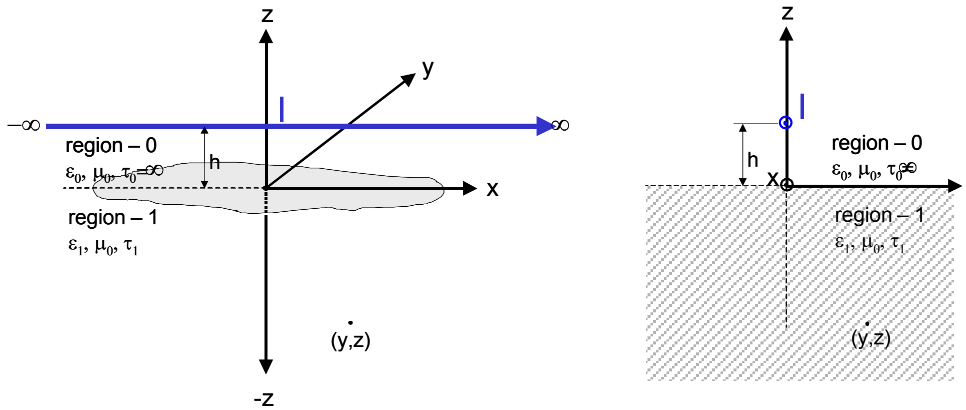


**Figure 3 Infinite Length, Harmonically Time Varying Horizontal Current Drive Over a Conductive Half-Space.**

The current drive is harmonically time varying and is directed along the positive x-axis at height, h, above it. The upper half space (region - 0) has infinite resistivity and the lower half-space (region - 1) has resistivity, $\tau_1$. If one neglects displacement current and relates current density, $i_x(x,y,z)$ and electric field, $E_x(x,y,z)$, in region-1 through, $E_x(x,y,z) = \tau_1 i_x(x,y,z)$, then the current density in the lower half-space, region-1, can be determined to be

$$E_x(y,z) = \frac{ik\varsigma_0}{\pi}\int_0^\infty \frac{e^{qz}e^{-uh}}{u+q}\cos uy\,du$$

where $k = \omega\sqrt{\mu_0\varepsilon_0}$ , $q = \sqrt{u^2 + ip^2}$ , $p^2 = \frac{\omega\mu_0}{\tau_1} = \frac{2}{\delta_1^2}$ , $\delta_1 = \sqrt{\frac{2\tau_1}{\omega\mu_0}}$ .

If the line current source is brought to the surface of the conducting homogeneous half-space, where h=0, integrating this result for y=0 to get the horizontal electric field immediately below the current source yields

$$E_x(y=0,z) = \frac{\tau_1 I}{\pi}\frac{1}{\delta_1^2}\left\{\left[(1+i)\frac{1}{\left(\frac{z}{\delta_1}\right)} + \frac{1}{\left(\frac{z}{\delta_1}\right)^2}\right]e^{-(1+i)\frac{z}{\delta_1}} - i2K_0\left[(1+i)\frac{z}{\delta_1}\right] - (1+i)\frac{1}{\left(\frac{z}{\delta_1}\right)}K_1\left[(1+i)\frac{z}{\delta_1}\right]\right\}$$

where $K_0$ and $K_1$ are modified Bessel functions. Note that we are now using positive z in the downward direction in the formula.

## Results

The models for diffusion coupling presented in the previous section are compared with the measured electric field. Using an effective soil resistivity of 80 Ω-m, the analytic model plotted in Figure 4 matches very closely the horizontal (P-directed) electric field measured with a parallel current drive. The correlation between model and measured data is extremely good from 10 to 100 kHz. This confirms that the major coupling mechanism from the surface to the underground cavity is field diffusion coupling. The measured data is contaminated by 60 Hz resonances and clutter below 1 kHz for this polarization. There is a deviation from the model of coupling beneath an infinite line, at frequencies below 1 kHz, where the measured data stays at a constant level of approximately 0.0006 V/m/A, whereas the analytical model predicts a downward slope. Much of this deviation can be attributed to the field caused by the DC component from the finite spacing of the ground rods. An estimate of this component of the electric field is shown below 1 kHz where the skin depth is much larger than the depth to the measurement antennas. A comparison of the average of the P-directed electric field measurements from P2 to P8 with the analytic diffusion model is shown in Figure 5. The average field is a more meaningful value to compare since it has local variations removed. The amplitude and shape show amazing correlation. The measured electric field was normalized by the current in the drive wire on the surface, so that the units are V/m/A.

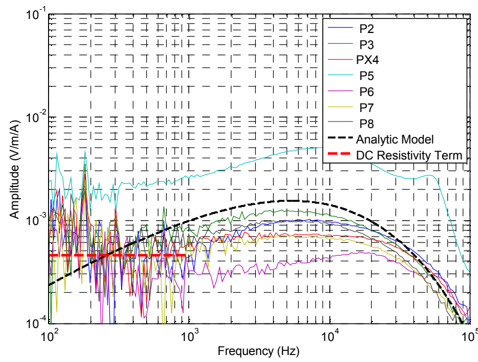


**Figure 4 P-directed Electric Fields compared with the diffusion model with an effective resistivity of 80 Ω-m.**

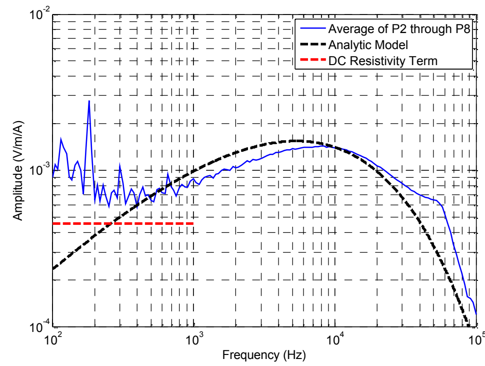


**Figure 5 Average of P-directed fields from P2 to P8 compared with diffusion model.**

## Conclusions

This series of experiments

- Very good quality data, well above noise floor
- Influenced by 60Hz and resonance clutter signals
- Clutter can be reduced by decreasing IF bandwidth, which increases measurement time
- Very good correlation between model and measured data.

## Acknowledgment


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